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Sunday, October 25, 2009

Our great…grandmother was a proton-powered rock

I've just read a very compelling theory of the origin of life. This pegs my "that explains so many things!" meter in a very big way. Alkaline vents -- the tame cousins of black smokers -- were common underneath earth's early oceans, but were chemically different than today. They were a chemical engineer's utopia: high temperatures and pressures, iron-sulfur mineral catalysts, a substantial proton gradient (alkaline vent water to soda-water-like ocean) and vast amounts of surface area formed by microbubbles. A new theory posits that Peter Mitchell's revolutionary discovery, proton-gradient manufacture of ATP, "the energy currency of life", was the original energy source of life, and that early evolution from primordial nucleic acids to the common ancestors of archaea, bacteria, and ourselves occurred in these sea-vent microbubbles. A proton gradient across a membrane simply means that one side is more acidic (it contains more naked protons) and the other side is more alkaline (it contains more water molecules missing a proton, called ~~"hydroxyl radicals"~~ hydroxide ions).

Because of Mitchell's discovery we now know that all known life uses membranes with proton gradients across them to convert energy into ATP molecules. Wherever the energy comes from -- from light, from carbohydrates stolen from other organisms (i.e. eating food), wherever -- in every living thing it gets converted into a proton gradient that then is tapped to manufacture ATP. In higher animals ATP is made from a proton gradient that is in turn made from "burning" blood sugar with oxygen, and this ATP powers our muscles and brains. In plants ATP is central to photosynthesis: light striking chlorophyll generates a proton gradient, and that proton gradient is used to manufacture ATP, which in turn is used to make sugars and other plant carbohydrates. In all life ATP powers the energy-using chemical reactions needed to make proteins, DNA, and RNA, the complex chemicals of life. (For biochemists reading this, relax, this is a summary: I've necessarily left out a very large number of complex steps, many still not fully understood).

The new theory of the origin of life recognizes that proton gradients existed on a massive scale in alkaline vents. The primordial, carbon-dioxide-rich oceans were acidic like Coca-Cola: they contained too many protons. These soda-water oceans were out of balance with the alkaline vent water, which contained water molecules with protons missing (hydroxide ions). Protons streamed across this gradient, with the protons from the soda-water ocean filling up the proton-deficient hydroxide ions to create normal water molecules. This stream of protons was a massive energy source that could be tapped to drive vast numbers of energy-consuming chemical reactions. Large amounts and varieties of chemicals were made on the vast surface areas of the microbubbles, eventually leading to the immensely complex chemicals and reaction pathways (metabolisms) that became life.

When, much later, plants evolved, they pulled almost all of the carbon dioxide out of the air and oceans, converting it into hydrocarbons and oxygen. Then animals evolved that could breath the oxygen, "burning" it with carbohydrates from eating the plants. Yet these very different energy sources get converted by plants and animals alike into the same thing -- proton gradients across

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membranes which are used to make ATP, the energy currency of life.

Ironically, we humans by burning fossil fuels are putting a small fraction of this ancient carbon dioxide which plants removed from the air and oceans back into the air, where it not only may be causing a bit of global warming, but is also dissolving back into the oceans and turning them a bit more acidic -- a tiny step back in the direction of the primordial conditions in which carbon dioxide concentrations were vastly higher than our puny modern levels, making the origins of life possible.

The theory's ten-step recipe for life:

1. Water percolated down into newly formed rock under the seafloor, where it reacted with minerals such as olivine, producing a warm alkaline fluid rich in hydrogen, sulphides and other chemicals - a process called serpentinisation.

This hot fluid welled up at alkaline hydrothermal vents like those at the Lost City, a vent system discovered near the Mid-Atlantic Ridge in 2000.

2. Unlike today's seas, the early ocean was acidic and rich in dissolved iron. When upwelling hydrothermal fluids reacted with this primordial seawater, they produced carbonate rocks riddled with tiny pores and a "foam" of iron-sulphur bubbles.

3. Inside the iron-sulphur bubbles, hydrogen reacted with carbon dioxide, forming simple organic molecules such as methane, formate and acetate. Some of these reactions were catalysed by the iron-sulphur minerals. Similar iron-sulphur catalysts are still found at the heart of many proteins today.

4. The electrochemical gradient between the alkaline vent fluid and the acidic seawater leads to the spontaneous formation of acetyl phosphate and pyrophospate, which act just like adenosine triphosphate or ATP, the chemical that powers living cells.

These molecules drove the formation of amino acids – the building blocks of proteins – and nucleotides, the building blocks for RNA and DNA.

5. Thermal currents and diffusion within the vent pores concentrated larger molecules like nucleotides, driving the formation of RNA and DNA – and providing an ideal setting for their evolution into the world of DNA and proteins. Evolution got under way, with sets of molecules capable of producing more of themselves starting to dominate.

6. Fatty molecules coated the iron-sulphur froth and spontaneously formed cell-like bubbles. Some of these bubbles would have enclosed self-replicating sets of molecules – the first organic cells. The earliest protocells may have been elusive entities, though, often dissolving and reforming as they circulated within the vents.

7. The evolution of an enzyme called pyrophosphatase, which catalyses the production of pyrophosphate, allowed the protocells to extract more energy from the gradient between the alkaline vent fluid and the acidic ocean. This ancient enzyme is still found in many bacteria and archaea, the first two branches on the tree of life.

8. Some protocells started using ATP as well as acetyl phosphate and pyrophosphate. The production of ATP using energy from the electrochemical gradient is perfected with the evolution of the enzyme ATP synthase, found within all life today.

9. Protocells further from the main vent axis, where the natural electrochemical gradient is weaker, started to generate

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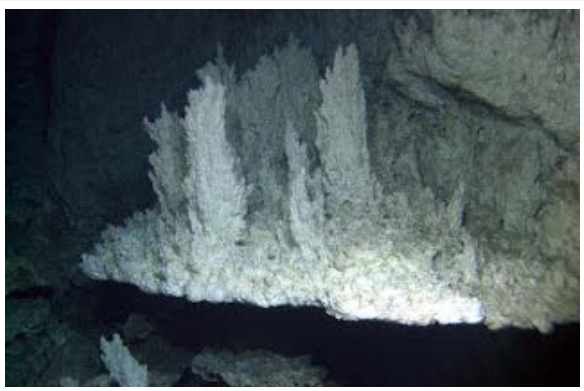
their own gradient by pumping protons across their membranes, using the energy released when carbon dioxide reacts with hydrogen.

This reaction yields only a small amount of energy, not enough to make ATP. By repeating the reaction and storing the energy in the form of an electrochemical gradient, however, protocells "saved up" enough energy for ATP production.

10. Once protocells could generate their own electrochemical gradient, they were no longer tied to the vents. Cells left the vents on two separate occasions, with one exodus giving rise to bacteria and the other to archaea.

More here.



Dendritic carbonate growths on the Lost City alkaline vent

Given the vast complexity of the genes and metabolism that would likely have existed in the common rock-bubble ancestor of archaea and bacteria, I suspect it will be a long time before all but the simplest of these steps are recreated in a lab. Still, this is by far the most compelling theory of the origin of life I've ever seen.

Peter Mitchell, discoverer of the proton-gradient manufacture of ATP, was a fascinating character: instead of entering the "publish or perish" and "clique review" rat-race of government-funded science, he dropped out of mainstream scientific culture and set up his own charitable company (nonprofit in U.S. lingo), Glyn Research Ltd. His discoveries were compelling enough to win over the early "he's a wingnut" skeptics and are now the centerpiece of our understanding of biological energetics. My essay "The Trouble With Science" suggests why this kind of independence is good for science. Here's more about Mitchell's theory of proton-powered life called chemiosmosis. The ten-step process above is the theory of William Martin and Michael Russell, and is an extension of Gunter Wachterhauser's iron-sulfur world theory.

Posted by Nick Szabo at 8:59 PM

8 comments:

tina said...

Here's a nice bio of Mitchell, only some of it technical: http://www.life.illinois.edu/crofts/bioph354/mitchell.html

10:14 AM

Eric Johnson said...

You have a mistake, or just a mental typo: hydroxyl radical (neutral charge), where you meant hydroxide ion, OH-

9:03 PM

nick said...

Eric, I indeed I had a mental blip in saying radical where I meant ion, thanks for the correction.

9:30 PM

Alrenous said...

You've also got a 'breath' instead of a 'breathe.'

Before this theory, I ran some sample numbers and concluded I had to be against biogenesis. Without absurd assumptions, I got a number on the order of 10^1000 trials to get free-floating life to reliably reproduce. (There are roughly 10^80 particles in the universe.)

With this idea, the cells already have walls, don't have to gather energy, and don't have to reproduce - the reaction just has to spread.

Plus, the chemistry is already similar to life as we know it.

11:56 PM

George Weinberg said...

This touches on a question from a couple posts back. It seems to me that, if this theory is correct, there are likely to be many airless, icy moons and planets with primitive life. But I don't see how that has any implications at all for intelligent life. Unless a world is suitable for photosynthetic life, I doubt it will ever develop multicellular life.

11:45 AM

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11:45 AM

nick said...

Alrenous, you're right, there have to have been simpler stages of evolution, the most primitive archaea or bacteria are far too complex to have just spontaneously formed even once in the universe. Just how much luck is required is an open question, because we are just now starting to get a handle on what those stages might of been (e.g. the speculative reconstruction 1-10 above is the best I've ever seen, but it is still speculative, and still quite incomplete, especially in step 5).

A very indirect estimate may be had by observing the lack of ETI (lack of artificial surfaces) in our galaxy or others that I have discussed. This touches on George's point -- it may well be that non-photosynthetic life is common and the Great Filter between the origin of life and civilization exists but occurs very early, with life almost always stopping short of tapping solar power. If the geological process of serpentization occurs underneath places like Europa and Enceladus, leading to widespread alkaline vents interfacing with acidic oceans, then primitive life may be common and more advanced life rare. The trouble with this theory is that, while these moons are likely far more common than habitable early-Earth-like planets, with the same serpentization process, the latter are still probably common enough for photosynthetic life to have arisen millions of times in our own galaxy alone if little luck was involved. Even broken down as in 1-10 above, there still seems to me a vast amount of luck required to get to life, enough to make it extremely rare but not universally impossible. The odds may be 1^-100 instead of 1^-1000 per trial, and there were more

than 1^100 trials available with second-generation "metallic" stars, but far less than 1^1000. There is still a great deal of handwaving (and most of Alrenous' 1^-1000 odds) in step 5 above.

A separate line of inquiry, "RNA world", has started to break down step 5 above into separate steps, but that work is still tentative and very little of it has yet been recreated in a laboratory, although I expect that eventually it will be. The biggest thing the new theory does is provide an ongoing and direct energy source to drive RNA world (by the direct formation of ATP or its more primitive forerunners). It probably makes RNA world quite a bit simpler -- nearly all the enzymes for forming lipids, and for tapping indirect chemical or photosynthetic energy sources, are no longer required, just a membrane with a proton gradient across it, an ATP synthase enzyme, and some RNA (and surely many details I'm leaving out, but the point is that DNA and the insanely complex modern metabolisms aren't required to get evolution going). And after all we are here, and so is and was archaea and bacteria, so biogenesis can't be completely impossible. We are just starting to get a handle on this, and I think the proton gradient membrane theory is a great step forward in our understanding.

5:15 PM

Billare said...

You should read the book "Power, Sex, Suicide: Mitochondria and the Meaning of Life" by Nick Lane. He explains this theory very competently in an engaging pop-sci way, and furthers argues that the endosymbiotic origin of mitochondria was the fundamental innovation that enabled multi-cellularity by 1: sequestering the products of these dangerous redox reactions from main cytoplasm and 2: freeing life from the fitness consequences of growing larger that bacteria still face today.

12:59 PM

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